REMARKS

In view of the foregoing amendments and the following remarks, allowance of this case is earnestly solicited.

Claims 1 and 28 have each been further amended to emphasize the relationship between the AC-voltage supply relative to the breakdown voltage of the gaseous substance being supplied into the discharge space as the plasma continues to be generated. The AC voltage is to be actively controlled to be at an amplitude equal to or less than 140% of the breakdown voltage of the gaseous substance thus providing a relationship that controls and reduces the temperature at which a substrate is treated by the plasma.

New claims 49 and 50 have been added. New claim 49 depends from claim 1 and sets forth one form of gaseous substance. New claim 50 sets forth a method for generating an APG plasma and for treating a substrate under controlled temperature conditions wherein as the process continues over time the gaseous stream, in the form of a carrier gas, is modified by the addition of further gases and that the amplitude of the AC voltage is itself variable and is modified to maintain a relationship to the breakdown voltage so as to be equal to or less than 140 % of the varying breakdown voltage of that changing gaseous substance.

The Obviousness Rejection

The examiner rejected claims 1-11, 14-25, 28-34, 36-43, 47 and 48 under U.S.C. 103(a) as being unpatentable over deVries ('632). Without repeating the lengthy discussion, a number of issues were found with the Examiner's reasoning and the citation to various portions of deVries '632. Consequently, this rejection is also traversed.

First, deVries ('632) relates to a wire-plate electrode arrangement and not to the presently claimed opposing plate electrode configuration. In particular, deVries ('632) uses a wire electrode opposite a drum electrode. Since the wire is of limited dimensions, it causes a substantive disturbance of the electric field. Field lines will be drawn to the wire and the wire thus provides a local field intensification. Locally near the wire electrode the field is very strong in comparison with the field strength elsewhere in the discharge space, which is near the drum electrode.

Breakdown voltage is dependent on the electric field and as a result breakdown will occur at a certain breakdown voltage between the electrodes. If the electric field is sufficiently strong there will be a sufficient concentration of ionized particles in order for breakdown to occur. Therefore, because of the use of a wire electrode breakdown voltages will be much lower that in the case of a flat surface electrode. DeVries ('632) at column 2, lines 39-42 confirms this when he states that breakdown of the electric discharge voltage will be reduced by using thin wire electrodes instead of parallel plate electrodes.

Second, the applied voltage is to be chosen in dependency on the breakdown voltage of the gaseous substance being provided into the discharge space, with the latter being an operational parameter that depends on the conditions in the discharge space. An objective is to reduce the temperature in the discharge space. This is accomplished by maintaining a relationship between the applied AC voltage and the breakdown voltage of the gaseous substance at a level where the applied AC voltage is at an amplitude equal to or leas than 140% of the breakdown voltage.

Third, while deVries ('632) does not specify breakdown voltages, breakdown voltages associated with such a wire-plate configurations relative to applied AC voltages can be

determined and the relationship there between will be much greater, by a factor of 3 or more, than the presently claimed "equal to or less than 140%" limitation.

Attachment A includes portions from a text by YuP. Raizer entitled "Gas Discharge Physics" that was published in 1991 (Springer Verlag 1991), specifically sections 12.7.3, 12.7.4, and 12.8.1.. The portion provided deals with the effects of non-uniformity of the field and the effect thereof on the breakdown voltage.

As is noted in the portion marked by "1" of Attachment A, where the electric field is non-uniform propagation of streamer discharges will be stimulated. This supports a conclusion that discharge in a wire-plate electrode configuration will occur at low voltages starting off as a series of streamers in multiple points on the wire. As noted at "2" field non-uniformity also reduces the breakdown voltage for a given distance between electrodes.

A reference value for breakdown voltage is provided in Fig. 12.13, noted at "5" and as note "3" suggests, breakdown voltage in a uniform field is equal to the tangent of the curve $V_t(r)$ at the point where r = R (here, R is 5cm; see the description of Fig. 12.13). As "r" decreases in Fig. 12.13, as noted at "4," i.e., following the horizontal or X axis to the left, non-uniformity increases, the slope of the curve decreases and the breakdown voltage likewise decreases. Of course, this difference may become large at high degrees of non-uniformity.

In wire-plate configurations discharges occur at low voltages and start off as a series of streamers at multiple points along a wire electrode. For such situations, discharges begin to occur at a breakdown voltage of 1 kV. DeVries ('632) discloses that he requires 3-5 kV for his applied AC voltage in order to cover the complete wire with a single plasma discharge. Thus, the difference between breakdown voltage and applied voltage is a factor of 3 or larger. Point "6" shows confirm this point that the differences between first streamer/corona discharge and glow discharge is illustrated at very small r and very high non-uniformity. Corona discharge

takes place fairly easily at low breakdown voltages while full breakdown through single glow plasma takes place at much higher voltages. In order to get a stable glow plasma, voltages must be much higher than the breakdown voltages for a corona/streamer discharge.

Note "7" in Attachment A confirms this non-uniformity effect and provides a comparison between wire-wire (rod-rod) and wire plate (rod-plane) configurations.

The wire to plate configuration of deVries ('632) gives rise to a high degree of non-uniformity as shown by Fig. 12.13 at a small wire diameter or small "r." The differences between the breakdown voltage and the applied AC voltage necessary for providing a glow discharge are large, for example a factor or three (3) or more. Thus, the fact that deVries ('632) uses a wire to plate configuration, does not recognize at all the desirability of reducing heat or treatment temperatures, does not teach or suggest any relationship between breakdown voltages and applied AC voltages, and does not suggest a low percentage relationship that should be maintained between the breakdown voltages and applied AC voltages. These factors collectively render deVries ('632) an ineffective reference and it is respectfully submitted that deVries ('632) does not render the claimed invention as being obvious.

Consequently, the inventor recognized that temperatures in the discharge space can be controlled by using a plate-plate electrode configuration and by maintaining a relationship between the amplitude of the AC-voltage being supplied and the breakdown voltage of the gaseous substance being used as the plasma is being generated. Specifically, that the amplitude of the applied AC-voltage is to be regulated in dependency on the breakdown voltage, the latter being an operational parameter that depends on the conditions in the discharge space. By actively controlling the applied AC-voltage at a level equal to or less than 140% of the breakdown voltage the inventor found that the dissipation energy can be reduced

and the temperature in the discharge space can thereby be controlled to thus prevent thermal damage to a thermoplastic polymer forming the substrate being treated.

It is submitted that since deVries '632 is directed to a different electrode configuration, does not mention temperature control anywhere, does not disclose any relationship between the amplitude of the AC-voltage and breakdown voltage of a supplied gas for any reason and suggests nothing about such a relationship which could be a basis for controlling temperatures within the discharge space, but rather teaches that the applied voltages are much larger than the low voltages associated with thin wire electrodes.

Thus, unless hindsight is used, and it cannot be, there is no basis for asserting that deVries'632 renders as obvious the claims now presented, and it is submitted that these claims now define patentably over deVreis'632. Notice thereof is respectfully requested.

In view of the above, it is believed that all of the claims now presented are in allowable form, and notice to that effect is respectfully requested. However, should the Examiner have any questions, or believe that some further discussion would prove helpful, the Examiner is urged to call the undersigned for such a discussion.

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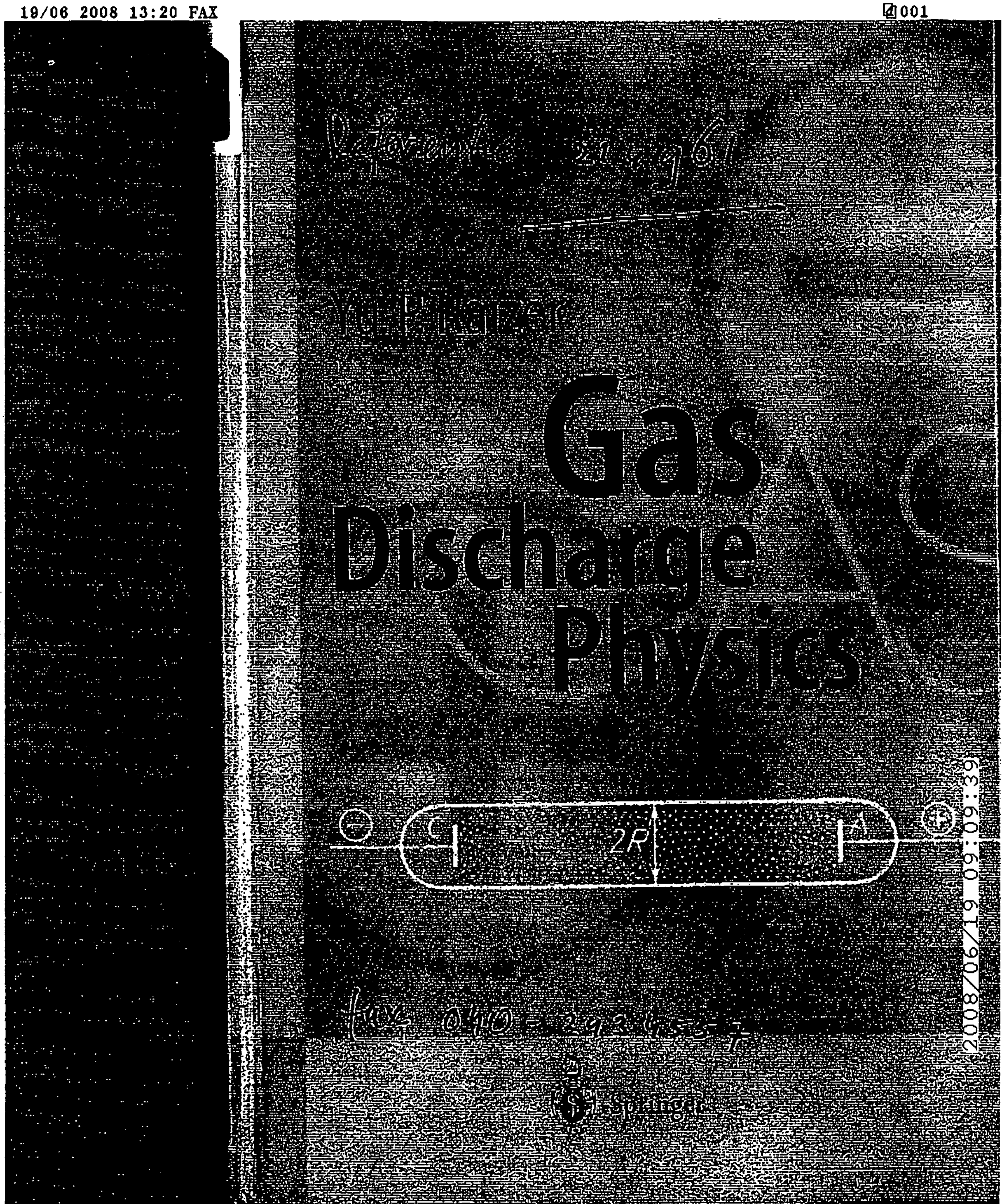

ATTACHMENT A

Yuri P. Raizer

704

Gas Discharge Physics

With 209 Figures

Springer

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12.7.3 Positive Streamer Insulated from the Anode in a Nonuniform Field (Streamer Corona)

The Dawson-Winn model was considerably improved by *Gallimberti* in 1972 [12.15], who was taken into account consistently the energy balance of processes involving the external field. Gallimberti also introduced an approximate description of photoionization, so as to eliminate the arbitrariness in prescribing the distance x_1 at which the avalanche is initiated. As in [12.14], it was assumed that only one "equivalent" avalanche is started. The positive sphere was again assumed insulated from the anode. The parameters of the streamer (N_0, r_0) change as it propagates in the nonuniform field. The energy balance equation expresses the fact that the work done by the external field on electrons compensates for the energy spent by electrons on ionization, excitation, attachment, on transfer to molecules, and also on the change in the potential electrostatic energy of the positive charge of the streamer head (both intrinsic and in the external field).

The fairly complicated equations were solved numerically for the specific conditions of corona in air. Figure 12.12 demonstrates excellent agreement with experimental results. The length of the streamer is about 11 cm, which the head covers in 10^{-7} s. The streamer moves over the first 5 cm (the region of especially strong field of 15 to 5 kV/cm) at a velocity of about 2×10^8 cm/s. The streamer stops where the field drops to 2 kV/cm. The number of positive charges in the head reaches the maximum $N_0 \approx 1.6 \times 10^9$ ($eN_0 \approx 2.5 \times 10^{-10}$ C).

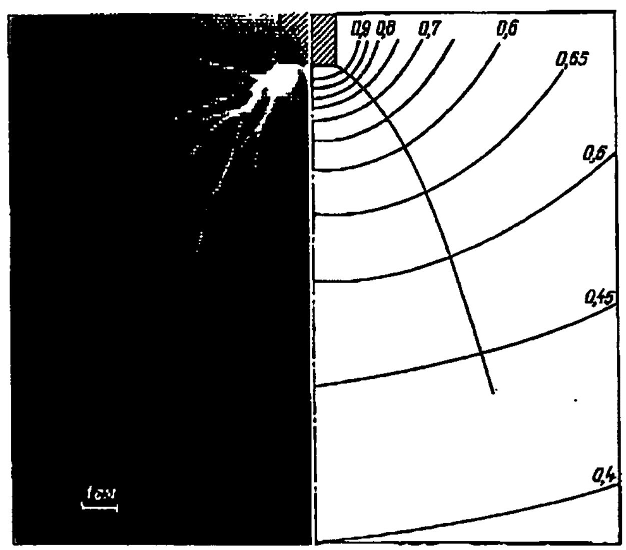

Fig. 12.12. Streamer moving from a positive rod 2 cm in diameter to a plane at a distance of 150 cm [12.15]. Constant voltage, 125 kV. *Right:* results of calculations; equipotential surfaces are shown; numbers on the curves give the fraction of applied voltage measured from the plane electrode. *Left:* photograph of streamers under the conditions of calculations

A numerical Monte Carlo procedure was developed for the approximation of two equivalent avalanches that are randomly initiated at different points of the angle sector near the streamer head [12.16]. This computer simulation produced a branching zigzag pattern of streamers under the same conditions; it resembled the photograph even more.

12.7.4 External Field Necessary for the Propagation of a Streamer

It is clear from the arguments above that the growing streamer must be supplied with energy; this function is fulfilled by the applied field, which does work on the electrons. This can be interpreted macroscopically as the energy released by the *streamer current*. The streamer current in the approximation of a concentrated charged head moving at a velocity v is given by formulas (12.6′, 6). If $N_0 \sim 10^9$, $v \sim 10^8$ cm/s in a long discharge gap of $d \sim 1$ m, then the average current is $i \sim 10^{-4}$ A, and if the gap is narrow, $d \sim 10$ cm, then $i \sim 10^{-3}$ A. The power $iV = eN_0vE$ is spent on ionization, on electron and vibrational excitation of molecules, and an attachment compensation. If the average energy spent on producing one electron is w, then $eN_0vE = n\pi r_0^2 vw$, where the charge density is $n \approx 3N_0/4\pi r_0^3$. The external field required to supply the energy to sustain the streamer is $E_s \approx w/er_0$, which satisfies the obvious condition $eE_s r_0 \approx w$.

The radius r_0 of the charged head and of the streamer channel is found from the condition of self-sustainment of the head in the strong field it creates and depends very little on the external field. If in air $w \approx 50$ eV and $r_0 \approx 10^{-2}$ cm, we obtain an estimate $E_s \approx 5$ kV/cm. A detailed calculation [12.15] for the case of a homogeneous field yielded $E_s = 7$ kV/cm. 1

These figures are in reasonable agreement with experimental data. According to [12.17], in dry atmospheric-pressure air we find $E_s \approx 4$ kV/cm. As reported in [12.18], the average external field that was necessary to sustain the steady growth of a streamer in air in the experiment was $E_s \approx 4.7$ kV/cm, almost independently of gap width and field nonuniformity. In technical grade nitrogen (up to 2 % O_2), $E_s \approx 1.5$ kV/cm; in Ar, $E_s \approx 0.4$ kV/cm (all at 1 atm.). The value of E_s is very sensitive to attachment, which removes electrons from the process. To multiply electrons up to the required level N_0, high energy expenditure is necessary.[3] Thus an admixture of O_2 to Ar increases E_s from 0.4 to 2.3 kV/cm at an O_2 content of 10 %. On the other hand, if air is heated to 1000 K, electrons are liberated from negative ions and E_s falls from 4.7 to 0.7 kV/cm [12.18]. The necessary field also increases as the humidity is raised. At a water vapour content of 2×10^{-5} g/cm^3, E_s is greater by a factor of 1.5 than in dry air [12.17].

[3] This may reflect the reduction of conductivity in the streamer channel (see Sect. 12.7.7), although this certainly has no place in the theory of the self-sustaining streamer heads.

breakdown has been observed only in inert gases. It seems that if the model of the ideally conducting streamer remains meaningful at all, it may hold only for inert gases.

12.7.8 Plasma Decay and the Radius of a Streamer Channel

The conductivity of the channel in air decreases rapidly as we move away from the streamer head. Actually, the plasma in the channel decays even in nitrogen (where attachment does not occur) if the external field is not much greater than the limiting field for the streamer propagation, $E_s \approx 1.5\,\mathrm{kV/cm}$ at $p = 1\,\mathrm{atm}$. The field behind the head does not exceed the external field and the corresponding $E/p = 2\,\mathrm{V/cm\,Torr}$ is too low for the ionization of the cold nitrogen (Sect. 8.7.7). Over the period $t \sim 10^{-5}\,\mathrm{s}$ during which a streamer passes across a meter-wide gap, electrons recombine to a density $n_e \sim (\beta t)^{-1} \sim 10^{12}\,\mathrm{cm}^{-3}$ from an arbitrarily higher initial value. A decrease in the conductivity of the channel (the more important, the longer the channel and the more uniform the external field) prevents the streamer breakdown of long uniform gaps.

Despite a certain similarity, a streamer channel with weakly ionized nonequilibrium plasma cannot be likened to the positive column of a glow discharge. Ionization processes in the discharge column balance out the loss of charge and the plasma in the column is self-sustained. The streamer channel is rather a "passive" plasma trace left behind the advancing self-sustained streamer head. The trace radius (channel radius) r is presumably determined by ambipolar diffusional expansion of the plasma from its initial size, that is, from the streamer head radius $r_0 \approx 3 \times 10^{-3}$–$10^{-2}\,\mathrm{cm}$ (Sect. 12.7.1). The seemingly unchanging "thinness" of a long channel creates the false impression of an inherent channel radius. In reality, the trace simply has not had enough time to expand significantly: at $D_a \approx 2\,\mathrm{cm^2/s}$, the increase of the radius over a time $t \sim 10^{-5}\,\mathrm{s}$ is $r - r_0 \approx \sqrt{D_a t} \approx 4 \times 10^{-3}\,\mathrm{cm} \approx r_0$.

The preservation of the radius of the initial perturbation of the growing plasma channel in the calculation [12.22] (mentioned in Sect. 12.7.7) is caused by the field build-up in the neighborhood of the channel; the spreading due to diffusion is negligible. The authors choose such a high value of the external field, $E \approx 40E_s$, that the ionization in the channel greatly exceeds the recombination.

12.8 Breakdown in Long Air Gaps with Strongly Nonuniform Fields (Experimental Data)

12.8.1 Effect of Field Nonuniformity on Breakdown Voltage

2

Field nonuniformity reduces the breakdown voltage for a given distance between the electrodes. This is illustrated in Fig. 12.13, where the measurements were conducted at the industrial frequency of 50 Hz. The nonsteady nature of the field makes practically no difference, because the half-period of $10^{-2}\,\mathrm{s}$ is long in com-

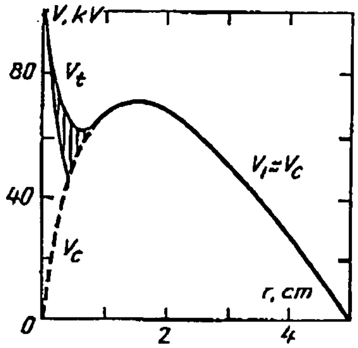

Fig. 12.13. Voltages of corona ignition V_c and of breakdown V_t in an air gap between concentric cylinders as functions of radius of the inner electrode; outer electrode radius $R = 5$ cm. (Amplitude of 50 Hz ac voltage is plotted.) The region of enhanced sprad in breakdown voltages is shaded [12.9] 5

parison with the time scale of breakdown.[6] Since the polarity of electrodes is alternating, the breakdown occurs at the polarity that facilitates it (see below). 3 The tangent to the curve $V_t(r)$ at $r = R$, with the slope of 32 kV/cm, roughly corresponds to the breakdown of plane gaps of the same size $d = R - r$ in uniform field. As r decreases, that is, as the degree of nonuniformity is enhanced, the threshold curve $V_t(r)$ deviates more and more downwards from the tangent. 4 The mean breakdown field $E_{av} = V_t/(R - r)$ diminishes monotonically in comparison with the level 32 kV/cm. The reason for this effect of nonuniformity is that any breakdown criterion includes the coefficient of enhancement of primary avalanches, $\int \alpha\, dx$, which is very sensitive to the distribution $E(x)$ owing to the steeply climbing curve $\alpha(E)$. The distribution of the field in comparison with the uniform picture increases the enhancement at preserved $\int E\, dx$, or decreases the potential difference at constant enhancement. We have already encountered this effect several times (Chap. 8).

Figure 12.13 is illustrative in another aspect, as well. The range of voltages $V_c < V < V_t$ over which a corona burns contracts as r increases, and the degree of field nonuniformity decreases. If the field is not too nonuniform, $r/R \gtrsim 0.1$, no corona develops: increasing the voltage on the electrodes leads straight to the breakdown of the gap. If, however, the radius of the electrode carrying the corona is very small (very high nonuniformity), the difference between the corona initiation and breakdown potentials, $V_t - V_c$, becomes large. 6

7 The effect of the degree of field nonuniformity on breakdown voltage is also revealed by the fact that it is easier to produce breakdown between a rod and a plane than between two rods, at the same separation d. The corresponding threshold voltages (also at 50 Hz) are plotted in Fig. 12.14 for gaps of d up to 10–12 m. The rod was a rectangular metal bar of square cross section, of 1/2″ sides. For the same d, the capacitance of the rod-plane gap is greater than that of the rod-rod gap, because the volume occupied by the field is greater. Therefore,

[6] In order to eliminate the effect of the rate of voltage build-up during the "switch-on" period in measurements of dielectric strength of a gap for dc or for time-dependent (not pulsed) fields, the electrode voltage (or the amplitude of the 50-Hz voltage) is raised gradually, over a time of up to several minutes (Sect. 12.8.4).

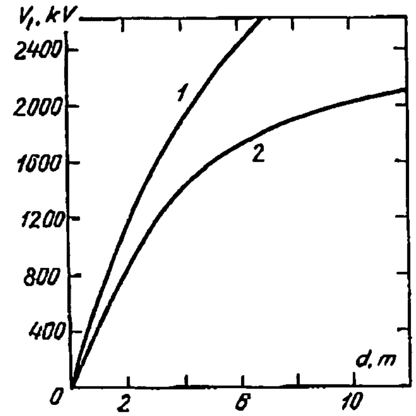

Fig. 12.14. Amplitude of breakdown voltage at $f = 50$ Hz in an air gap of length d. *(1)* rod–rod, *(2)* rod–plane gap [12.7]

the electric charge on the rod is greater at the same voltage in the former case; furthermore, the field at the tip and in most of the gap is higher.

From the standpoint of field distribution, the rod-rod gap of d at V is equivalent to a rod-plane gap of $d/2$ at $V/2$. This factor affects the values of the respective breakdown parameters in the conditions of complete symmetry produced by the oscillating field. Thus the rod-rod gap of $d = 6$ m has $V_t = 2400$ kV, while the rod-plane gap of $d = 3$ m has $V_t = 1200$ kV. At smaller separations this equivalence rule does not hold as strictly: $V_t = 1850$ kV in the rod-rod gap of $d = 4$ m, and $V_t = 850$ kV in the rod-plane gap of $d = 2$ m. Nevertheless, the deviation is not large.

12.8.2 Effect of Polarity

The breakdown threshold in a constant field depends very strongly on the polarity of the "active" electrode (Fig. 12.15; the same rod geometry). In the case of a negative rod, the breakdown voltage is roughly twice that of the positive one. This is a result of the difference between the conditions for the development of avalanches and streamers at the active electrode. The avalanches at the *rod anode* travel to it from the outside; as they come nearer, they enter the region of

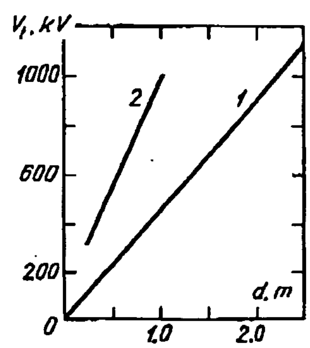

Fig. 12.15. Threshold voltages in air gaps of length d between a rod and a plane. *(1)* positive rod (anode), *(2)* negative rod [12.9]